PL-TR-96-2251

IMPROVED UNDERSTANDING OF BROADBAND Lg/P RATIO AND ITS APPLICATION TO DISCRIMINATING EARTHQUAKES FROM EXPLOSIONS, INCLUDING DECOUPLED SHOTS

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26 September 1996

Scientific Report No. 1

DEPARTMENT OF ENERGY
Office of Non-Proliferation
and National Security
WASHINGTON, DC 20585

PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
HANSCOM AFB, MA 01731-3010

SPONSORED BY
Department of Energy
Office of Non-Proliferation and National Security

MONITORED BY
Phillips Laboratory
CONTRACT No. F19628-95-C-0176

This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	26 September 1996	Scientific No. 1

4. TITLE AND SUBTITLE

Improved Understanding of Broadband Lg/P Ratio and Its Application to Discriminating Earthquakes from Explosions, Including Decoupled Shots

5. FUNDING NUMBERS

PE 69120H
PR DENN TA GM WU AP
F19628-95-C-0176

6. AUTHOR(S)

Indra N. Gupta

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Multimax, Inc.
1441 McCormick Drive
Largo, MD 20774

8. PERFORMING ORGANIZATION REPORT NUMBER

MM-02-96-001

9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

Phillips Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010
Contract Manager: Delaine Reiter / GPE

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

PL-TR-96-2251

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An understanding of the mechanism of generation of Lg from underground nuclear explosions is essential for seismic monitoring and source discrimination. Near-source scattering of explosion-generated Rg into S appears to be responsible for the low-frequency Lg from nuclear explosions at both NTS and Kazakh test sites. The source of Rg has a strong compensated linear vector dipole (CLVD) component, and the prominent low-frequency null in the observed Lg is due to Rg from a CLVD source. In this study, the dependence of spectral nulls on source parameters is first investigated by analyzing Lg from a large number of NTS explosions. Most Lg spectra indicate prominent nulls at frequencies which vary with shot depth and are in remarkably good agreement with those expected from Rg due to a CLVD source at about one-third the shot depth. Analysis of low-frequency Lg from explosions at Kazakh, Lop Nor, and Azgir test sites also show that the observed spectral nulls depend strongly on shot depth and local velocity structure, and a comparison with theory provides useful source information, including accurate shot depth. By providing an improved understanding of Lg and its usefulness for obtaining source information, these results make an important contribution to seismic monitoring of the Comprehensive Test Ban Treaty.

14. SUBJECT TERMS

Lg, regional phases, scattering of Rg, source discrimination, seismic monitoring, NTS, Kazakh, Lop Nor, CTBT

15. NUMBER OF PAGES

36

16. PRICE CODE

17. SECURITY CLASSIFICATION	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF THIS PAGE	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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SUMMARY

This annual report deals with a study of the low frequency Lg from explosions at the Nevada, Kazakh, Lop Nor, and Azgir Test Sites. An understanding of the mechanism of generation of Lg from underground nuclear explosions is essential for seismic monitoring and source discrimination at regional distances. Earlier studies have suggested that near-source scattering of explosion-generated Rg into S is responsible for the low-frequency Lg from nuclear explosions at both NTS and Kazakh test sites. A recent analysis of regional data from NTS explosions has indicated that the source of Rg waves must have a strong compensated linear vector dipole (CLVD) component and the prominent low-frequency spectral null in the observed Lg is due to Rg from a CLVD source. An objective of this research is to investigate the spectral nulls and other characteristics of the low-frequency Lg from explosions at various test sites so that the scattering mechanism and its potential for obtaining useful source information can be fully exploited. The dependence of spectral nulls on shot depths and other source parameters is first investigated by analyzing Lg from a large number of Yucca Flats (NTS) explosions, with known ground truth, recorded at several broadband stations. Methods of analysis include narrow bandpass filtering, network-averaging, spectral ratios, and comparison of results with those from synthetics. Most Lg spectra indicate prominent nulls at frequencies which appear to vary systematically with shot depth and are in remarkably good agreement with those expected from Rg due to a CLVD source at about one-third the shot depth.

Low-frequency Lg from nuclear explosions at Kazakh, Lop Nor, and Azgir test sites are analyzed by using regional data from mostly broadband and a few other (short-period and long-period) stations, including WMQ and stations belonging to the NRDC, KNET and the ILPA array. The observed spectral nulls, although generally not as strong as for the NTS shots, are in most cases distinct and identifiable. The null frequencies appear to depend strongly on shot depth and local velocity structure and a comparison with theory provides useful source information, including shot depth with an accuracy not possible by other methods. An effective CLVD source is present not only for Lg from NTS explosions but also for explosions from other test sites in significantly different geological environments. By providing an improved understanding of Lg from explosions and its usefulness for obtaining source information, these results make important contribution to seismic monitoring of the Comprehensive Test Ban Treaty.

INTRODUCTION

A clear understanding of the broadband characteristics of regional phases and their dependence on various near-source parameters must be obtained if successful seismic monitoring techniques developed in one region are to be used in other locations. Lg is often the largest seismic phase from both explosion and earthquake sources recorded at regional distances. Numerous studies have demonstrated the usefulness of Lg for detection, source discrimination, and yield estimation of underground nuclear explosions. However, a full understanding of the generation and spectral characteristics of Lg, essential for providing confidence in our ability to monitor nuclear test ban treaties, is largely lacking. Perhaps the most enigmatic aspect of Lg from explosions is their spectra's relative richness in low frequency energy compared to earthquake Lg spectra. Gupta *et al.* (1991, 1992) proposed a theoretical model suggesting that the near-source scattering of explosion-generated Rg into S makes a significant contribution to the low-frequency Lg. This mechanism explains why the low-frequency Lg from explosions is so large that it destroys the discrimination capability of Pn/Lg amplitude ratios at frequency of about 1 Hz. Most evidence for this hypothesis came from analysis of regional data from nuclear explosions at both Nevada and East Kazakh test sites. Independent support for this mechanism also came from an examination of the source spectra of Lg from East Kazakh and Novaya Zemlya explosions by Israelsson (1992), and from analysis of Lg spectral ratios from Yucca Flats (NTS) explosions by Patton and Taylor (1995).

In order to explain pronounced spectral nulls in the Lg spectra of several Yucca Flats (NTS) explosions, Patton and Taylor (1995) suggested that the Rg waves must originate mainly from a compensated linear vector dipole (CLVD) source and the prominent low-frequency null is due to an excitation null in Rg for a buried CLVD source. It follows that an analysis of the low-frequency Lg may be useful for estimating source depth if one can establish a relationship between the centroid depth of the CLVD source and the explosion depth. Modeling of the observed Lg with the help of synthetics may also provide other source and near-source information. Rg is stronger for shallow sources such as mining explosions and rockbursts than for deeper sources such as earthquakes. The main objective of this research is to investigate broadband characteristics of regional phases, especially Lg, under various tectonic settings. The results contribute to monitoring of a CTBT by providing a physical basis for regional discriminants, essential for improving their reliability and transportability from one region to another.

ANALYSIS OF LOCAL AND REGIONAL DATA FROM NTS SHOTS

A comprehensive study of the generation of Lg from underground nuclear explosions and its dependence on source and near-source parameters requires analysis of large amounts of data for which detailed ground truth information is available. This is mostly true of only the NTS explosions although limited source information is now available for several Kazakh Test Site (KTS) explosions. Therefore, we first investigated regional and other data from NTS shots (Gupta and Zhang, 1996).

The time-varying spectral characteristics of the observed seismic arrivals are examined by using narrow bandpass filtering (NBF) which provides amplitudes for various values of group velocity and period. The NBF technique, described in detail by Seneff (1978), has been employed by several investigators (*e.g.* Kafka, 1990) to study Rg from shallow sources. The group velocity curves are computed by using a moving zero-phase Gaussian filter. The period axis represents the central period of the filter and the velocity axis is simply epicentral distance/travel-time. The filter is applied at each period, the energy envelope computed, and the energy envelope curves are represented in the form of a two-dimensional matrix which is contoured.

Digital, broadband data from several NTS explosions recorded at both local and regional distances are available from Los Alamos National Laboratory (Edwards and Baker, 1993; Taylor, 1993). NBF analysis was first carried out on local data from the nuclear explosion, Metropolis (10 March 1990, m_b = 5.0, depth 469 m) at several recording stations, covering the distance range of 114 to 274 km (Edwards and Baker, 1993). Figure 1 shows locations of Metropolis, field deployment stations DM, MV, LM, and HD at local and near-regional distances (Edwards and Baker, 1993), Sandia National Lab (SNL) stations TON, DRW, NLS, and LDS, and Lawrence Livermore National Lab (LLNL) stations ELK, MNV, LAC, and KNB. Using the vertical component data from the intermediate-period system (which records velocity at frequencies above the seismometer period of 5 sec), results from four stations are shown in Figure 2. At the three short distances (Figures 2a, b, c), the direct fundamental-mode Rayleigh (which includes the short period Rg) are well recorded but the NBF results show sharp drop in amplitude for the shorter periods. A possible explanation is that, within a few km of the source, the shorter period Rg is scattered into S waves which travel with a velocity considerably higher than velocity of the shorter-period Rg. A spectral null at period of about 1.7 sec is observed in energy traveling with velocity of about 1 to 4 km/sec, which includes not only Rg but also S-wave group arrivals such as Sg, Lg and Sn. At larger distance (Figure 2d), the spectral null is clearly observed in Lg which has become the dominant phase because of greater attenuation with distance of Rg. The spectral null in the Rg-S wave group at shorter distances also appears in Lg at regional distances, indicating that the Rg spectrum is imprinted onto the scattered S waves. These results strongly support importance of the CLVD source and the near-source scattering of explosion-generated Rg into S waves and subsequently into Lg.

We also analyzed regional data from stations that recorded, in addition to Metropolis, two more Yucca Flats explosions, Texarkana (10 February 1989, m_b = 5.2, depth 503 m) and Tulia (26 May 1989, m_b = 3.7, depth 396 m), separated by about 5 km (Figure 3). NBF analyses of the vertical component, long-period data, with peak response at slightly less than 0.1 Hz (Taylor, 1993) from station TON are shown in Figure 4. Prominent spectral nulls in the S-wave group or Lg, with velocity of about 3 km/sec, are observed at periods of 1.5 and 1.3 sec for Texarkana and Tulia, respectively. NBF of Tulia recorded at DM also suggests a null at period of about 1.3 sec. The observed difference in null period for Texarkana and Tulia are likely to be due to several factors such as differences in their shot depths, medium velocities, and yield.

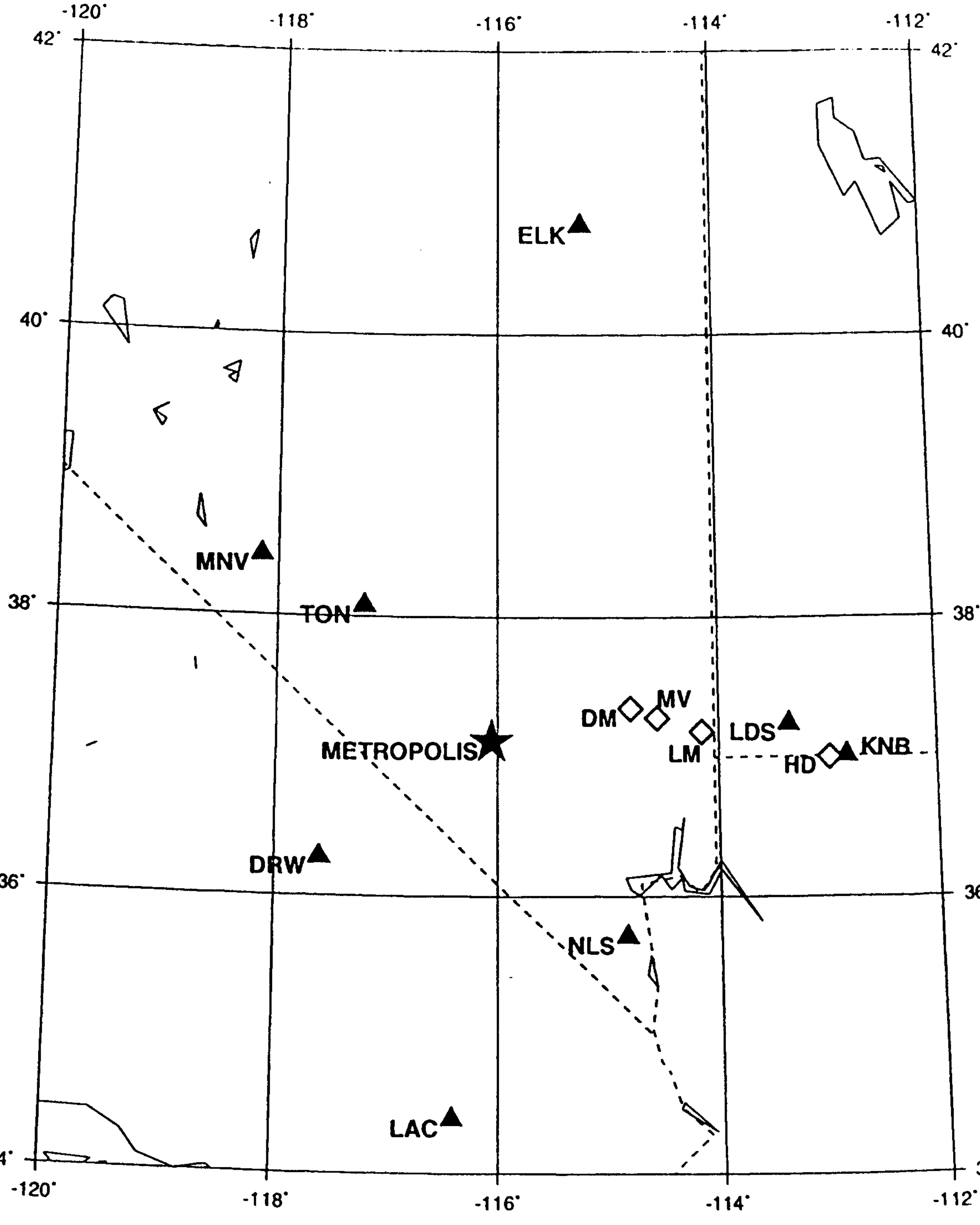

Figure 1. Location map of the underground explosion, Metropolis and local and regional stations providing data used in this study. Stations MNV, KNB, LAC, and ELK belong to the LLNL network and TON, DRW, NLS, and LDS are part of the SNL network.

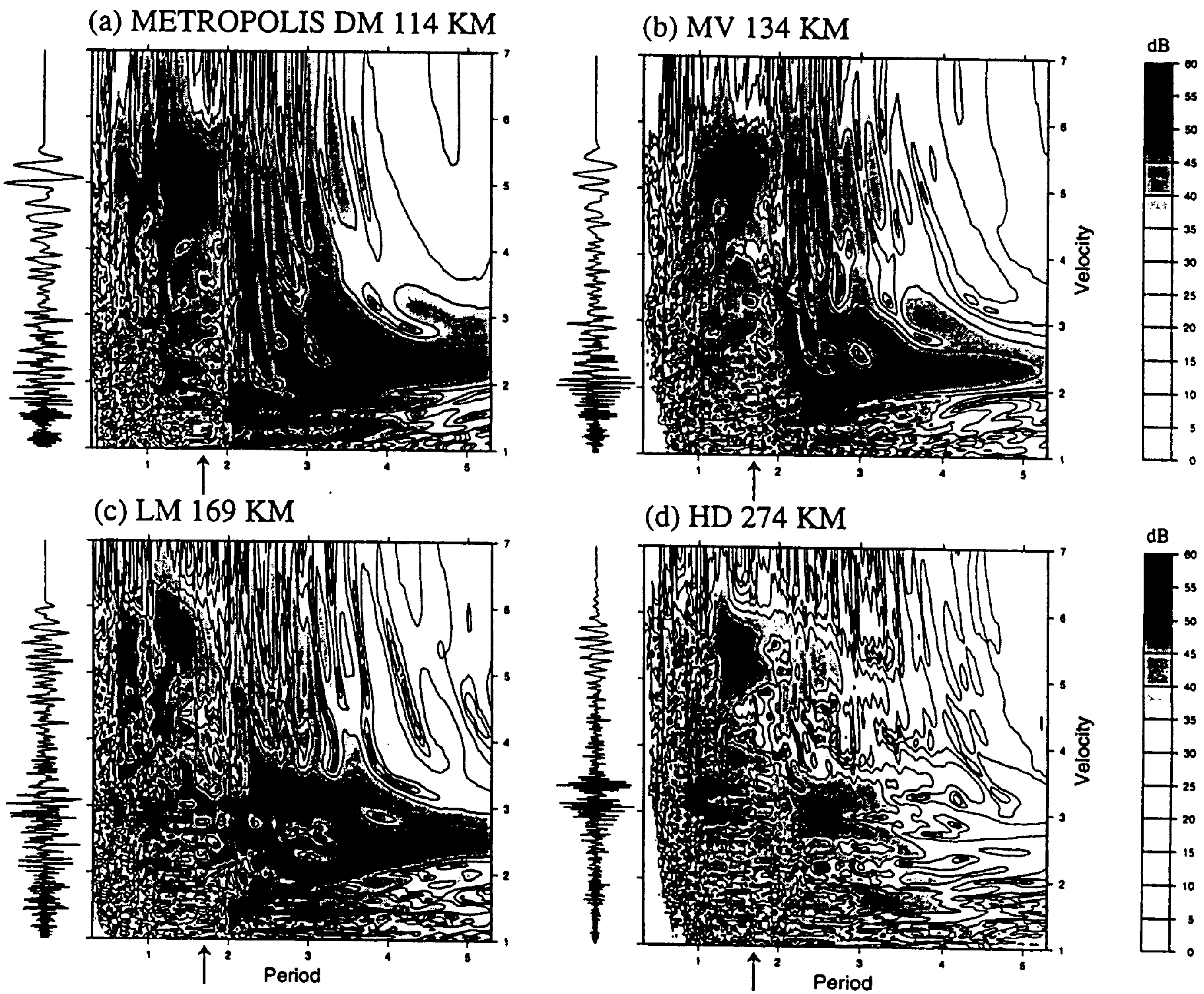

Figure 2. Narrow bandpass filtered records of Metropolis at four different distances indicating progressive (with distance) scattering of Rg into Lg and spectral null at period of 1.7 sec in both Rg and Lg.

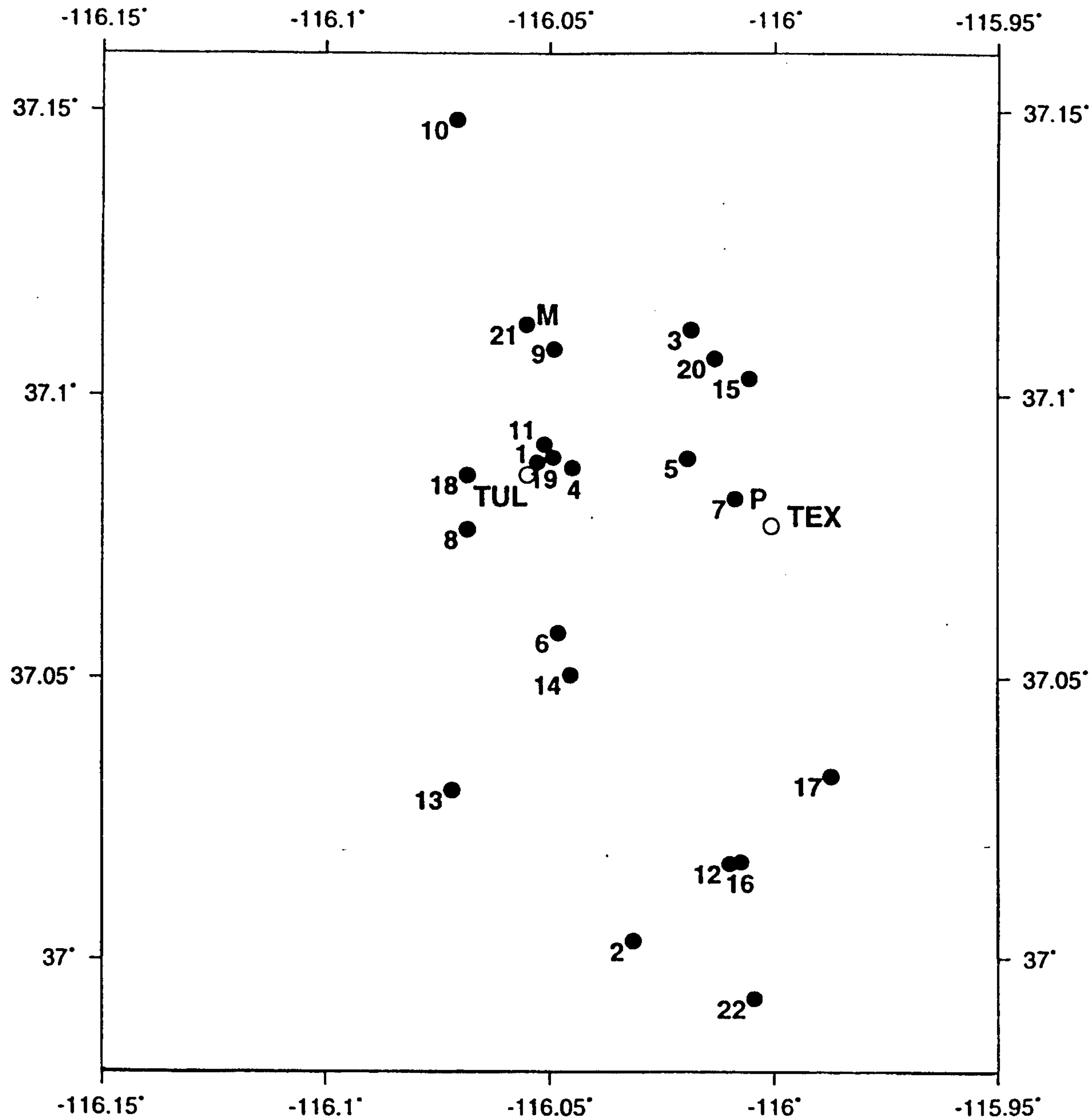

Figure 3. Location map of 22 underground explosions used in this study, including Metropolis and Paliza, denoted by M and P, respectively, with numbers corresponding to those in Table 1. Locations of two additional shots Texarkana and Tulia (denoted by TEX and TUL, respectively), are also shown.

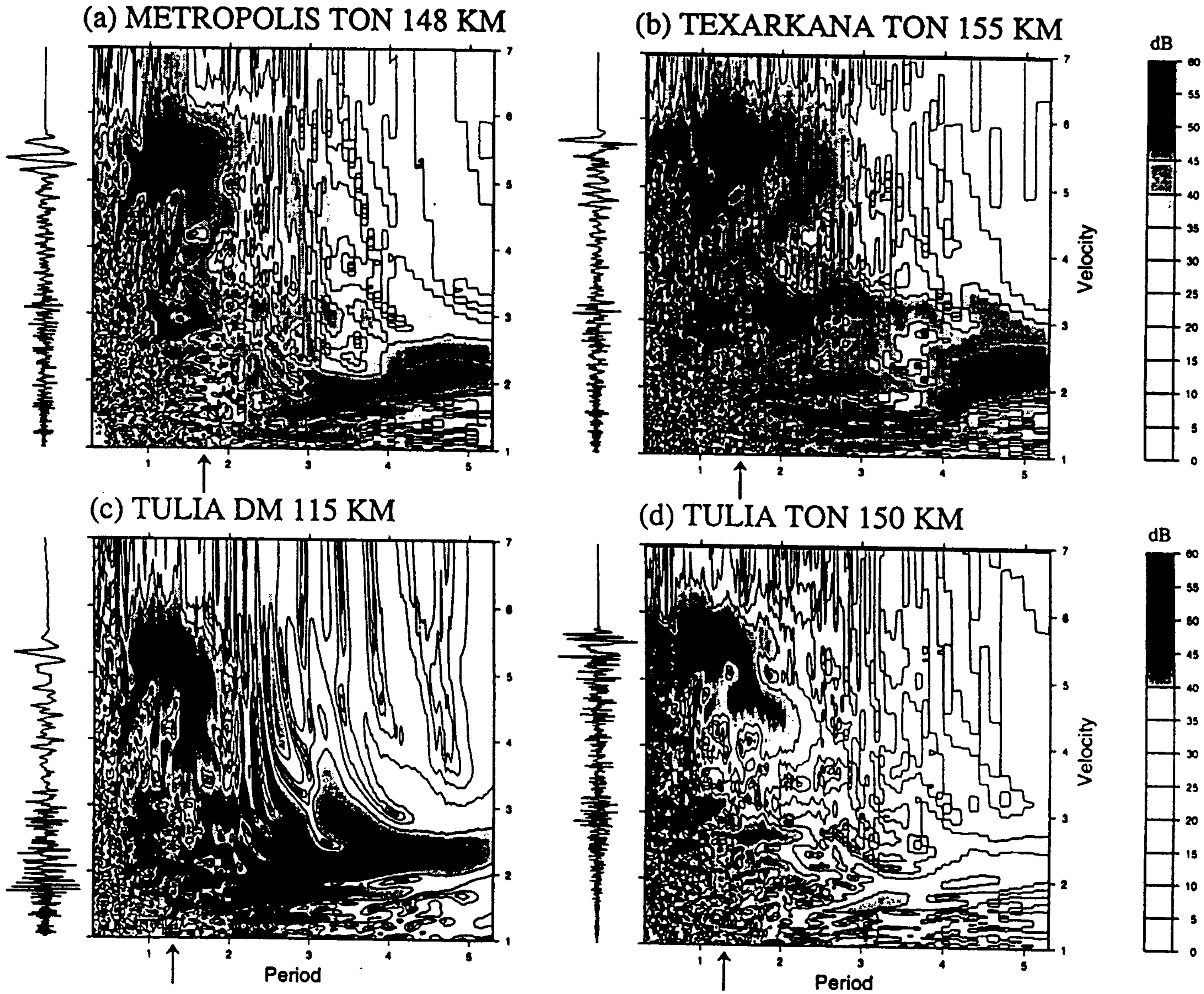

Figure 4. Similar to Figure 2 for the nuclear explosions Metropolis, Texarkana, and Tulia with shot depths 469, 503, and 396, respectively. The spectral nulls appear to vary with both shot depth and subsurface structure.

The dependence of spectral nulls on shot depths is investigated by analyzing Lg from 22 Yucca Flats explosions (Table 1 and Figure 3) recorded well at the four broadband stations (MNV, KNB, LAC, and ELK) of the LLNL network. Table 1 includes the overburden velocity (average compressional-wave velocity between the shot point and the surface measured by sonic logs) which suggests considerable lateral variation. Using 51.2 sec long Lg windows, multitapered spectra were obtained for each of the four stations and corrected for attenuation by using Lg(Q) values in Patton (1988). Network-averaged spectra were also obtained by averaging (on log scale) the four single-station spectra. As an example, results for Metropolis are shown in Figure 5 which indicates distinct nulls at each of the four stations. The average null frequency at about 0.68 Hz appears stable since the null frequencies show only a small variation from one station to another. Similar results based on use of the four SNL stations are shown in Figure 6 which again shows distinct nulls at each station and the average null frequency is again 0.68 Hz. The consistency of spectral nulls in Figures 5 and 6 rules out the possibility of these nulls owing their origin to factors such as site effects or multipathing.

Results from 8 shots, arranged in order of decreasing shot depth and recorded at MNV, are shown in Figure 7a whereas the LLNL network-averaged spectra are shown in Figure 7b. As expected, spectral nulls in the network-averaged spectra are considerably more distinct and reliable than those from a single station. The network-averaged spectra were used to determine the spectral null frequencies (included in Table 1). Both Figures 7a and 7b indicate an increase in the null frequency with decreasing shot depth but the increase in null frequency is at first small and much larger for shallower depths. It should be noted that the null frequencies in Table 1 also indicate some regional variation for shots with nearly the same shot depth. For example, the individual and average spectra for Paliza (Figure 8) show a spectral null at about 0.78 Hz whereas those for Metropolis, with shot depth differing by only 3 m, have a spectral null at 0.68 Hz (Figures 5 and 6). The main reason for this variation is probably the presence of significant lateral variation in the subsurface as also evidenced by the large (1.3 to 1.8 km/sec) variation in the overburden velocities (Table 1).

METROPOLIS (DEPTH 469 m), LLNL STATIONS

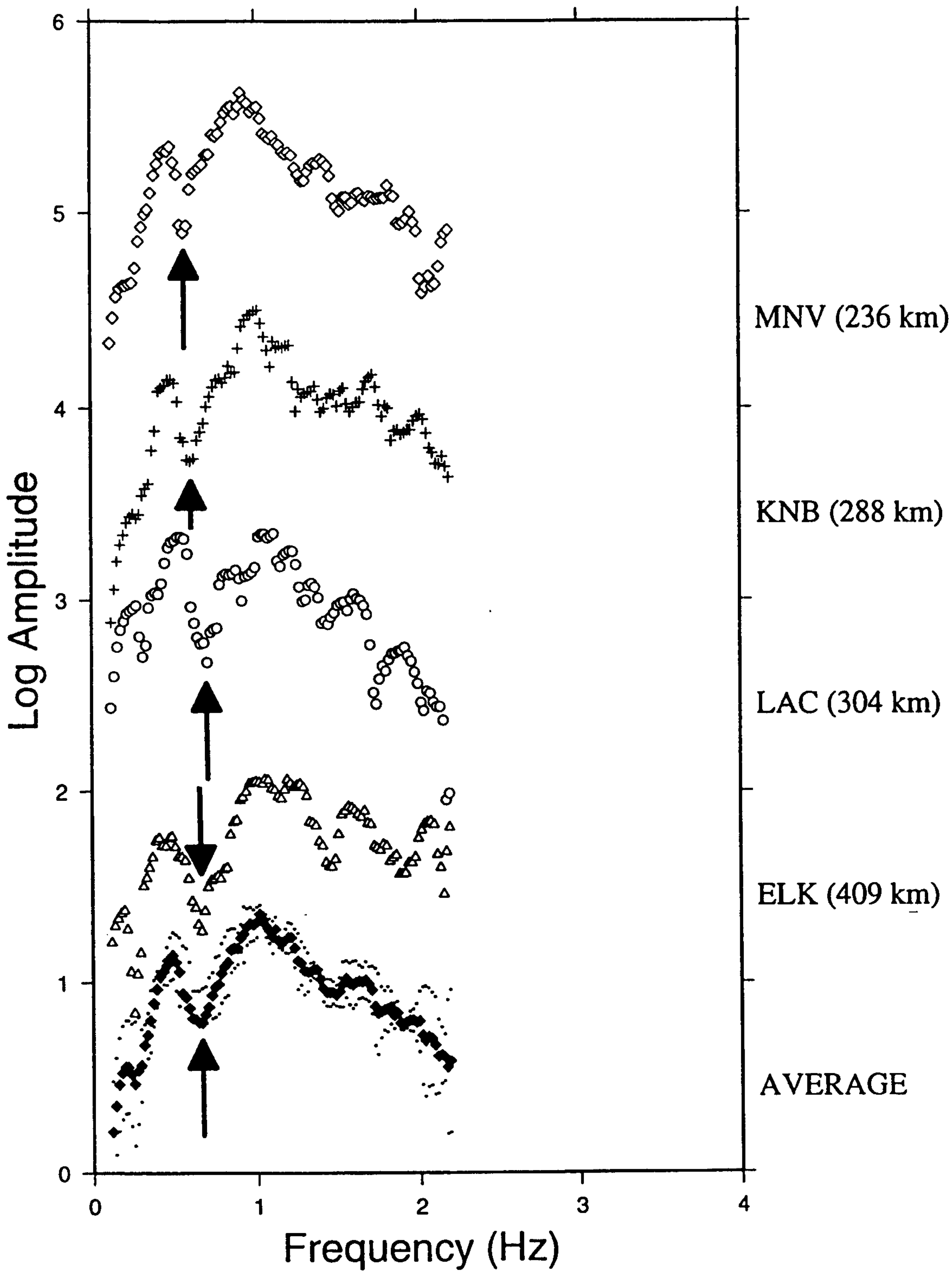

Figure 5. Single station and network-averaged Lg spectra, based on LLNL stations, for Metropolis, indicating a spectral null at frequency of about 0.7 Hz.

METROPOLIS (DEPTH 469 m), SNL STATIONS

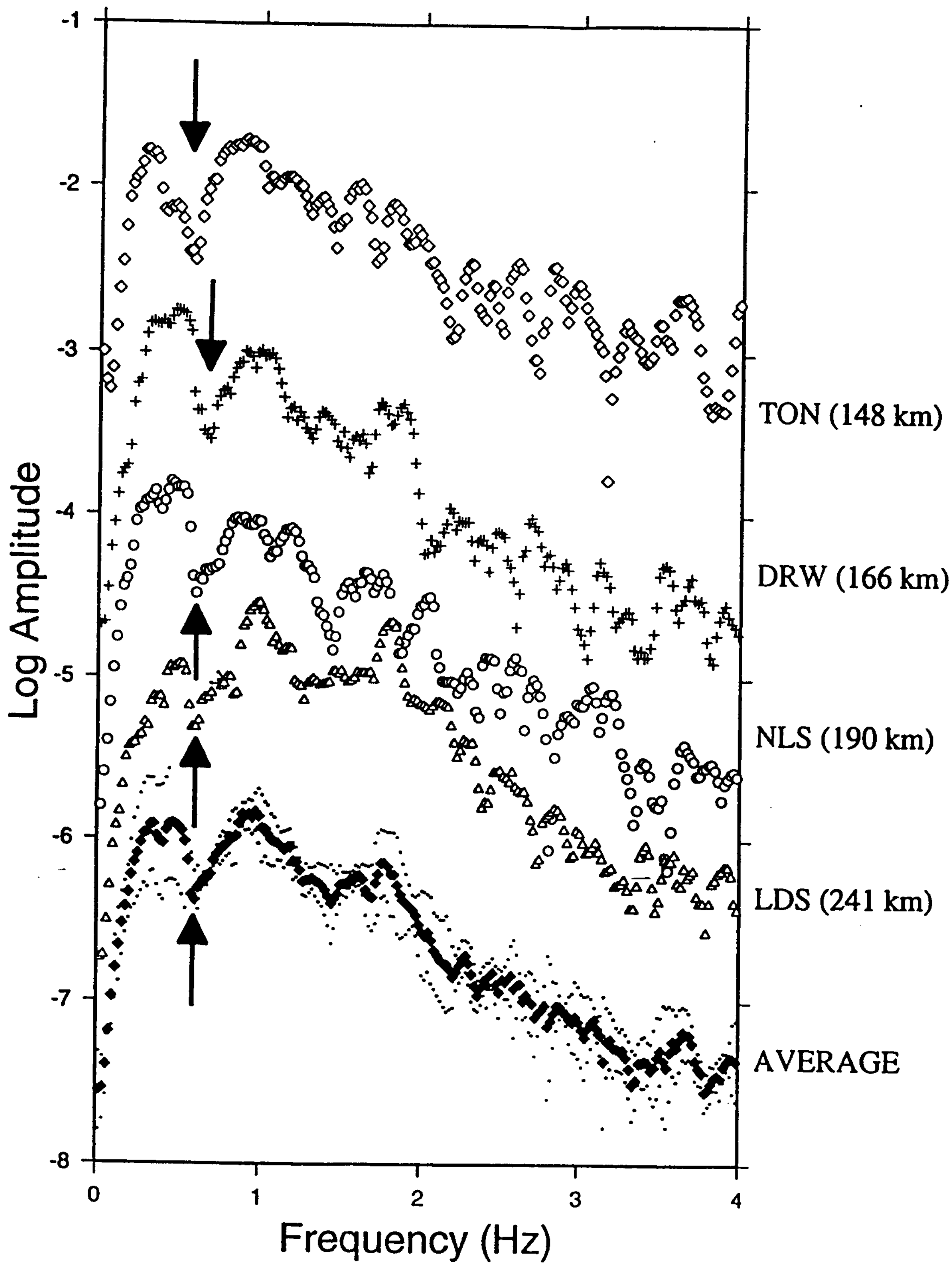

Figure 6. Single station and network-averaged Lg spectra, based on SNL stations, for Metropolis, again indicating a spectral null at frequency of about 0.7 Hz

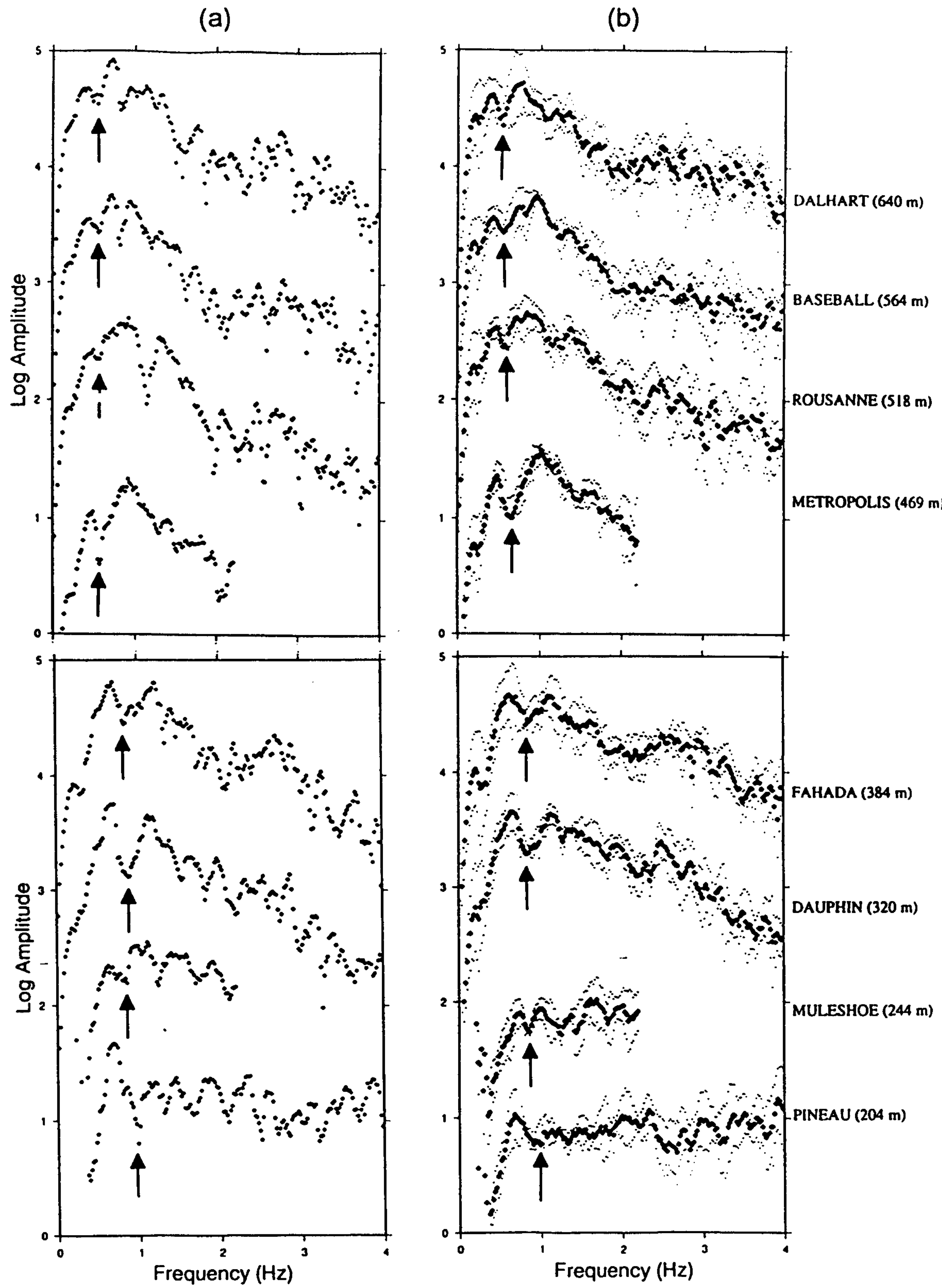

Figure 7. Spectra of Lg for 8 explosions at Yucca Flats with shot depths as indicated, based on (a) data from a single station, MNV, and (b) network averaged over all four LLNL stations, showing systematic variation of spectral null frequency (indicated by arrows) with shot depth.

PALIZA (DEPTH 472 m), LLNL STATIONS

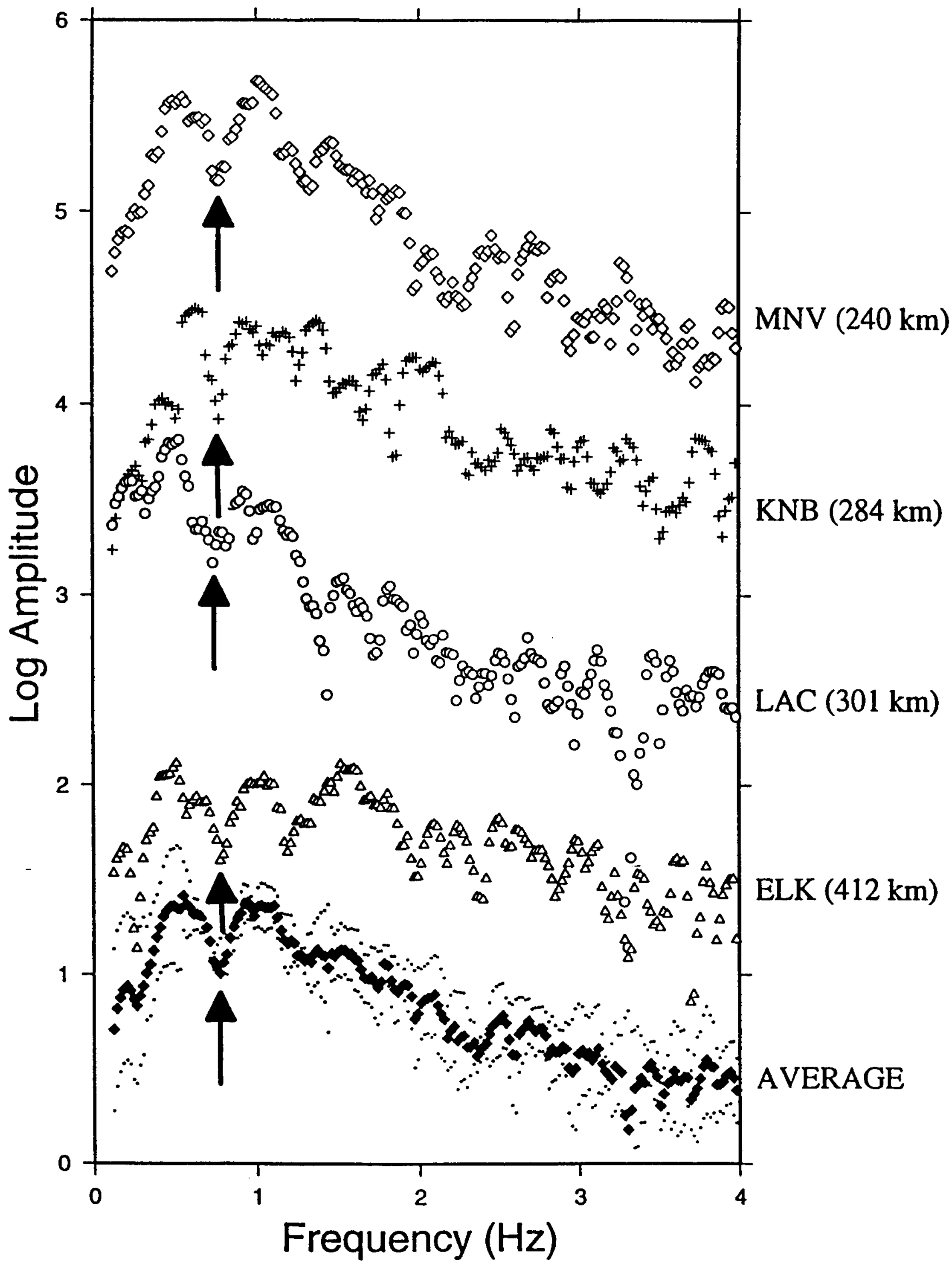

Figure 8. Single station and network-averaged Lg spectra, based on LLNL stations, for Paliza, indicating a spectral null at frequency of about 0.8 Hz.

Table 1: Yucca Flats Explosions and Associated Lg Null Frequencies

No	Date	Name	Depth (m)	Velocity (km/sec)	Frequency (Hz)
1	06 Sep 79	HEARTS	640	1.763	0.55
2	22 May 80	FLORA	335	1.257	0.85
3	14 Nov 80	DAUPHIN	320	1.420	0.82
4	15 Jan 81	BASEBALL	564	1.970	0.55
5	16 Jul 81	PINEAU	204	1.125	1.00
6	04 Sep 81	TREBBIANO	305	1.465	0.80
7	01 Oct 81	PALIZA	472	1.497	0.78
8	11 Nov 81	TILCI	445	1.600	0.80
9	12 Nov 81	ROUSANNE	518	1.580	0.60
10	03 Dec 81	AKAVI	494	1.730	0.82
11	28 Jan 82	JORNADA	640	1.695	0.53
12	17 Apr 82	TENAJA	357	1.310	0.86
13	10 Dec 82	MANTECA	413	1.610	0.90
14	11 Feb 83	COALORA	274	1.340	0.82
15	26 May 83	FAHADA	384	1.500	0.82
16	02 Aug 84	CORREO	335	1.305	0.84
17	21 May 88	LAREDO	350	1.600	0.91
18	30 Aug 88	BULLFROG	489	1.622	0.80
19	13 Oct 88	DALHART	640	1.770	0.56
20	15 Nov 89	MULESHOE	244	1.330	0.87
21	10 Mar 90	METROPOLIS	469	1.515	0.68
22	21 Jun 90	AUSTIN	351	1.370	0.85

For a homogeneous semi-infinite medium, one can determine (e.g. Aki and Richards, 1980) that the CLVD spectral null frequency occurs approximately at V/(16 h) where V is the P-wave velocity and h is depth of the CLVD source (Poisson's ratio of 0.25 is assumed). This means that the null frequency is inversely proportional to source depth and directly proportional to medium velocity. In order to understand the observed variation with depth of the Yucca Flats explosions, the wavenumber integration technique described by Herrmann and Wang (1985) was used for generating the Rg synthetics for vertically oriented CLVD sources at various depths. The crustal velocity model of Patton and Taylor (1995, Table 1, SMU Velocity Model) was used; the source was assumed to be an impulse. The epicentral distance was taken to be only 20 km since the Rg-to-S scattering is supposed to occur near the explosion source. Figure 9 shows the spectra of Rg for various depths of the CLVD source. It is interesting to note that the increase in the null frequency is slow at first but becomes much larger for shallower depths, remarkably similar to the observed variation in Figure 7. A comparison of the observed null frequencies (Table 1) with the theoretical results in Figure 9 suggests that, on average, depth of the CLVD source for each explosion is about one-third of its shot depth.

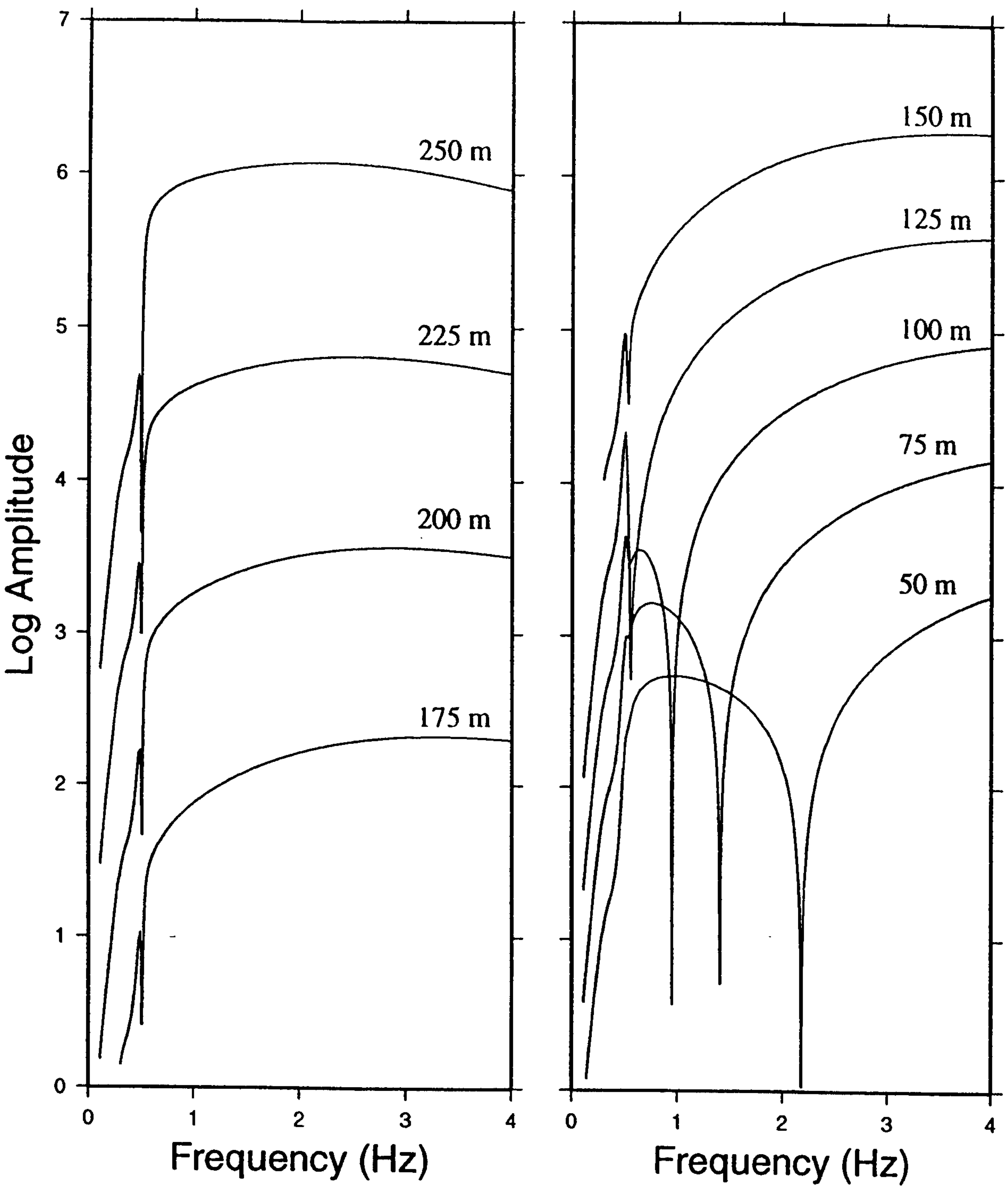

Figure 9. Spectra of Rg synthetics for CLVD source at various depths for crustal velocity model of Yucca Flats used by Patton and Taylor (1995). The increase in the null frequency with source depth is similar to that in Figure 7.

SPECTRAL NULLS IN Lg FROM KAZAKH EXPLOSIONS

Regional data from the Soviet underground nuclear explosion of the Joint Verification Experiment (JVE, 14 September 1988, $m_b = 6.03$) are available at the three Natural Resources Defense Council (NRDC) stations, KSU, KKL, and BAY. These three stations lie at epicentral distances of about 160 km east, 255 km southwest, and 255 km northwest, respectively. Details of the experiment, sample records, and instrumentation have been provided by Priestley *et al.* (1990). The long and short period seismographs consist of 15 and 1 sec free period seismometers, respectively. Results of NBF analysis of the vertical component long-period data from KKL and BAY and short-period data (after integration using the trapezoidal rule) from KSU (the long-period data at KSU had problems, William Walter, personal communication) are shown in Figures 10, 11, and 12, respectively. These three figures show severe attenuation of Rg for periods less than 1.2-1.3 sec and build-up of the shorter-period S arrivals suggests the scattering of shorter-period Rg into S or Lg. Group velocity of the scattered S is higher than that of Rg, indicating that scattering must take place near the source region. In each figure, a spectral null in Lg (velocity 3.0-3.5 km/sec) is observed at a period of about 0.7 sec.

Regional data from the JVE and several other East Kazakh nuclear explosions are also available at the broadband stations, WMQ (CDSN network) at distances of about 950 km from KTS. Spectral ratios of Lg from the JVE and the much smaller explosion of 12 March 1987, 87071 ($m_b = 5.31$), both recorded at WMQ (vertical component) so that path effects are minimized, are shown in Figure 13(a) for Lg windows of 76.8, 51.2, and 25.6 sec. Each of the three plots shows a spectral null at about 1.4 Hz which corresponds to the null at period of 0.7 sec observed in the NRDC regional data. Furthermore, the plots suggest a maximum at frequency of about 1.8 Hz which may be due to the shallower CLVD source associated with Lg from the smaller explosion, 87071. Spectral ratios of Lg from the explosion of 3 April 1987 (87093), with $m_b = 6.12$ (somewhat larger and presumably deeper than the JVE) and the smaller explosion 87071, shown in Figure 13(b), also indicate a spectral null at frequency of about 1.1 Hz, likely to be due to the CLVD source associated with the larger explosion 87093. Spectra of Lg (51.2 sec long windows) from 7 explosions from the southwest region of KTS, recorded at WMQ and arranged in order of decreasing m_b, with Q correction from Xie *et al.* (1996), are shown in Figure 13(c); these also suggest a systematic increase in the Lg null frequency with decreasing m_b which should be associated with decreasing shot depth, and therefore decreasing depth of the CLVD source. These results suggest that shot depth is important in defining the spectral null in Lg and a determination of the spectral nulls in Lg and comparison with theory should be useful for determination of shot depths and other source and near-source characteristics.

CHINESE TESTS AT LOP NOR

There is increased interest in nuclear explosions at the Lop Nor test site because, in contrast with the U.S., Russian, and French nuclear test sites, this test site has been active as recently as July 1996. Analysis of Lg from several Lop Nor shots recorded at stations belonging

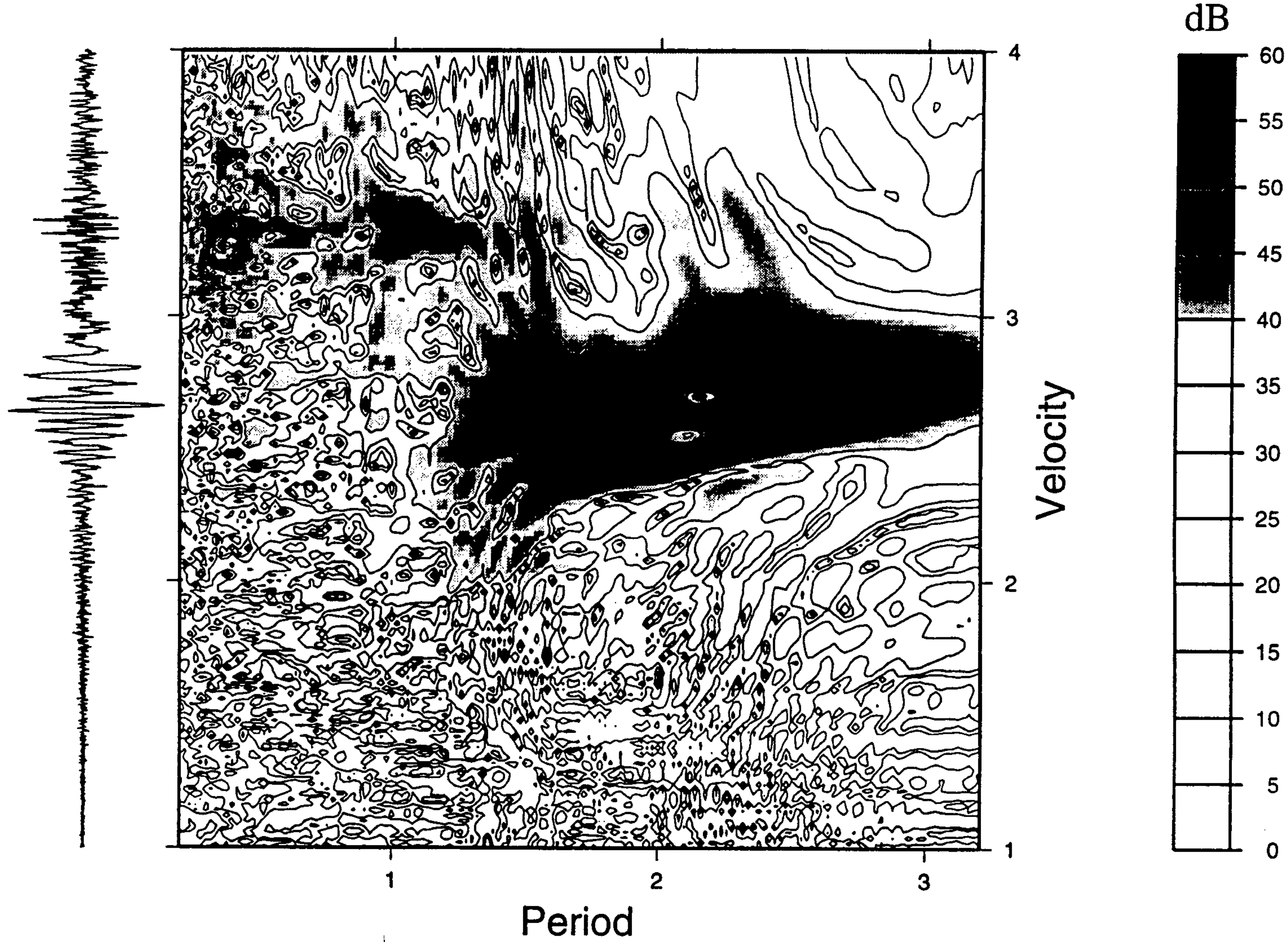

Figure 10. Narrow bandpass filtered record of the Soviet JVE shot of 14 September 1988 at the NRDC station, KKL indicating strong attenuation of Rg for periods less than about 1.2 sec and a spectral null in Lg at a period of about 0.7 sec.

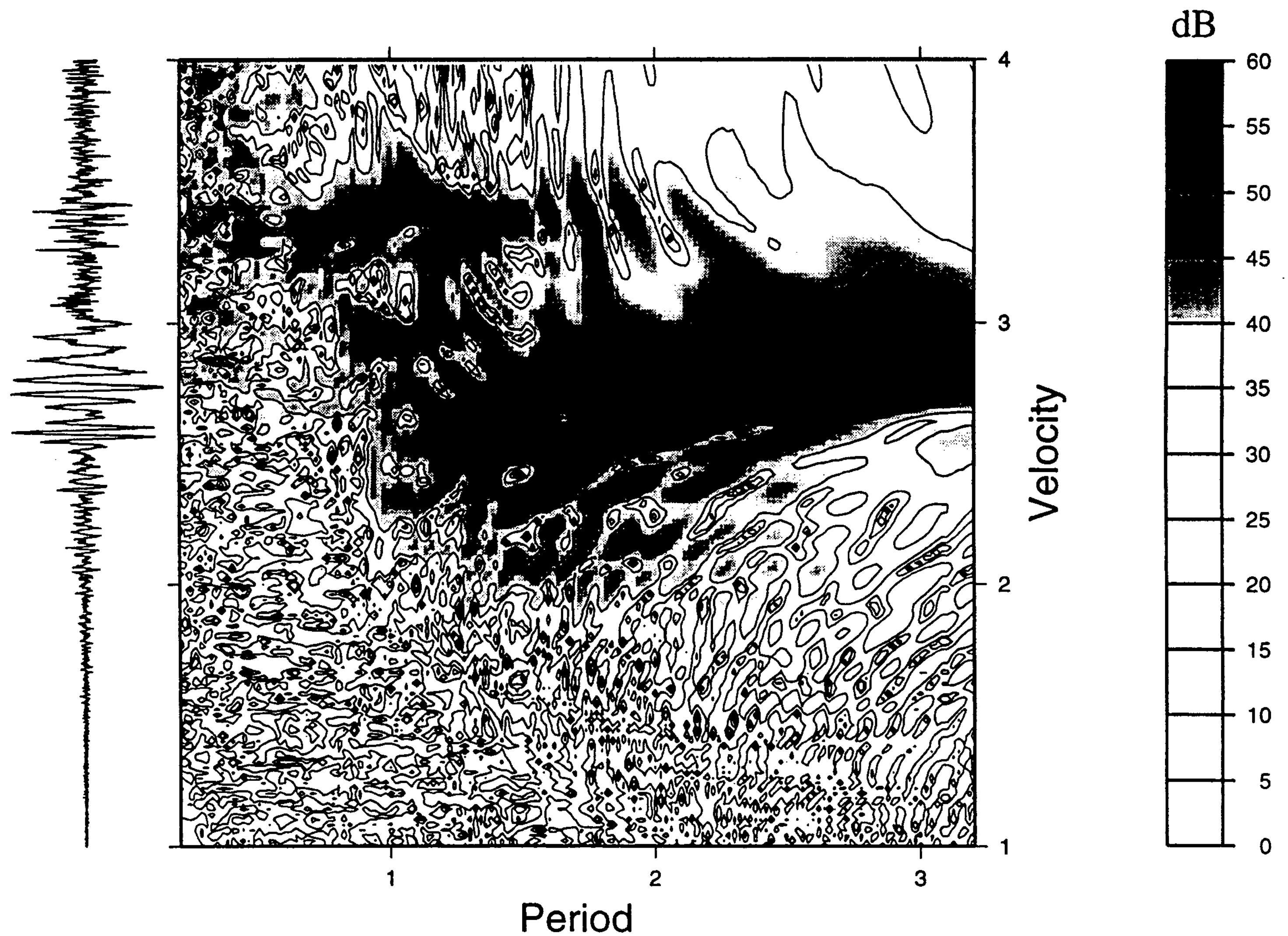

Figure 11. Narrow bandpass filtered record of the Soviet JVE shot of 14 September 1988 at the NRDC station, BAY indicating strong attenuation of Rg for periods less than about 1.1 sec and a spectral null in Lg at a period of about 0.6 sec.

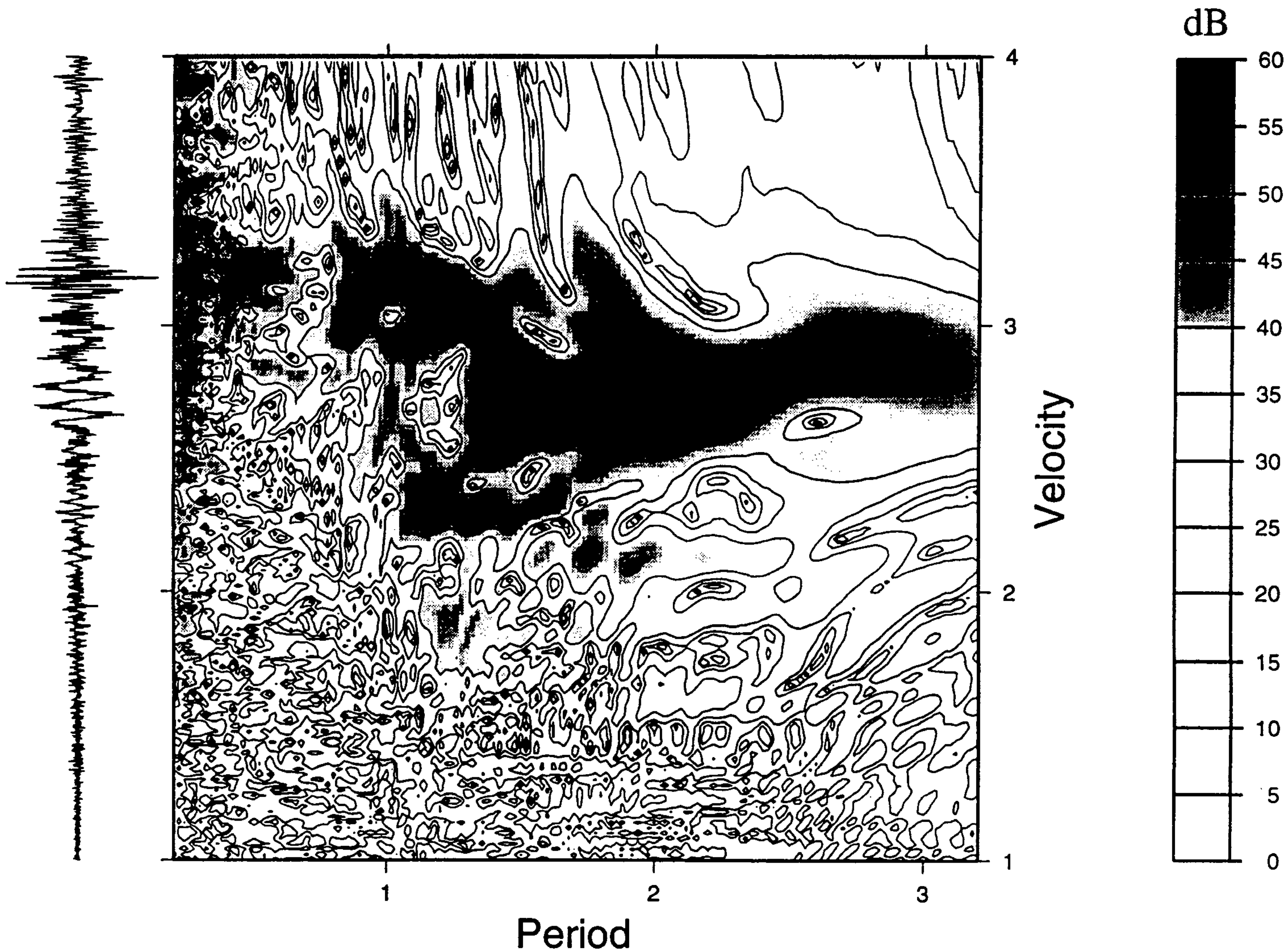

Figure 12. Narrow bandpass filtered record of the Soviet JVE shot of 14 September 1988 at the NRDC station, KSU indicating strong attenuation of Rg for periods less than about 1.0 sec and a spectral null in Lg at a period of about 0.7 sec.

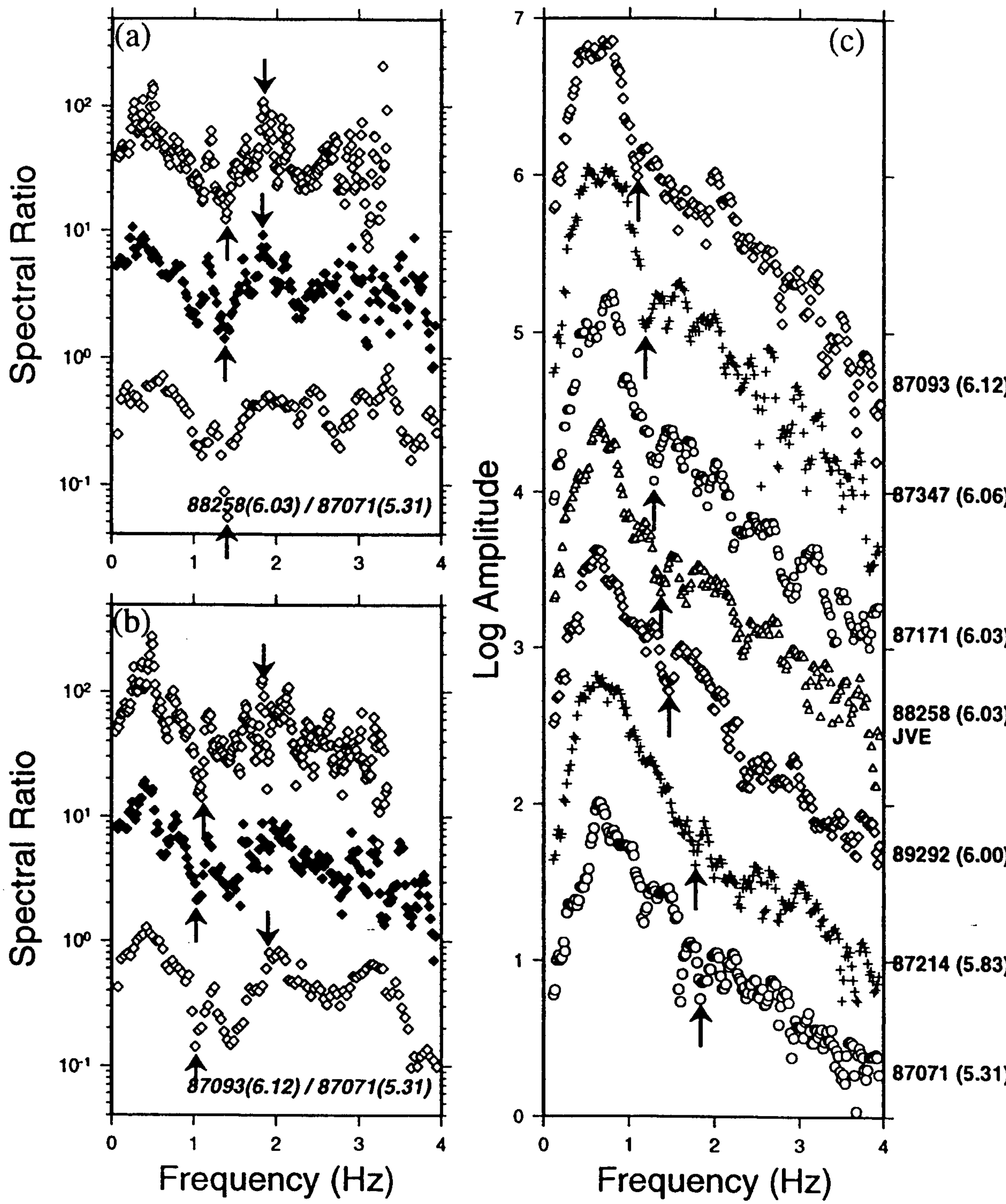

Figure 13. Lg spectral ratios for Kazakh shots recorded at WMQ (a) 88258(JVE)/87071 and (b) 87093/87071 for window lengths of 76.8 sec (top), 51.2 sec (middle), and 25.6 sec (bottom). Each of the three plots in (a) shows a spectral minimum at about 1.4 Hz and a maximum at about 1.9 Hz; plots in (b) indicate a spectral minimum at about 1.1 Hz. (c) Spectra of Lg for 7 Kazakh explosions suggesting a systematic increase in null frequency with decreasing m_b.

to the Kyrghizstan Network (KNET) showed distinct low-frequency nulls at most stations. Results for 5 shots recorded at the vertical-component broadband KNET station, AAK at epicentral distances of about 1150 km are shown in Figure 14. The individual spectra, with Q correction from Xie *et al.* (1996) (Figure 14a), and the spectral ratios (Figure 14b) indicate the same distinct spectral nulls and a general increase in frequency with decrease in magnitude. Moreover, the null frequencies are similar to those for Kazakh shots (Figure 13) for shots with similar magnitudes.

Matzko (1994) provided a detailed description of the geological structure and rock types at the test site. According to him, the largest shot of 21 May 1992 was emplaced in a shaft over 900 m deep and had a yield of about 1 megaton. Furthermore, the nuclear shots are fired in either vertically drilled shafts or horizontal tunnels but there is hard rock coupling in both areas and the Lop Nor test site is, in several respects, more similar to the KTS than the NTS. This provides a possible explanation for the similarity of the observed Lg null frequencies at KTS (Figure 13) and Lop Nor test site (Figure 14).

AZGIR PNE AT ILPA ARRAY

Regional data from the salt shot (PNE) of 18 December 1978 (m_b = 5.9) at Azgir (north of the Caspian Sea) are available at the ILPA array (Figure 15); see Grant *et al.* (1996). The vertical-component waveforms at two locations, IR1 and IR7 show considerably less energy in Lg than in Sn. A possible reason for the diminished Lg is the presence of mostly oceanic path through the Caspian Sea. Spectra of Lg and Sn windows, each 51.2 sec long and starting at velocities of 3.5 and 4.3 km/sec, respectively, are also shown in Figure 15. Not only the Lg spectra but also the Sn spectra indicate a prominent spectral null at frequency of about 1.1 Hz. It appears therefore that the source of the low frequency energy in the large Sn phase is the same as in Lg and the low-frequency energy in both phases originated from the near-source scattering of Rg into S.

DISCUSSION AND CONCLUSIONS

Our results fully support Patton and Taylor's (1995) contention that the spectral null in Lg at 0.55 Hz from three normal-depth explosions at the Yucca Flats is primarily due to a CLVD source. However, a few significant differences should be pointed out. The five Yucca Flats explosions used in their study lay close to each other (within about 3 km) and their observational and theoretical results for normal-depth explosions did not show much dependence on shot depth. Our study of low-frequency Lg from a large number of shots with considerable variation in shot depth, combined with theory, clearly indicate that shot depth and subsurface structure are important in defining the spectral null.

Our study of Lg from four distinct test sites indicates that near-source scattering of explosion-generated Rg is an important contributor to the low-frequency Lg from explosions at not only NTS but also in other regions of the world. Broadband data can be effectively used to determine the observed spectral nulls, especially if data from several stations are available so that site effects can be suppressed. Good agreement between observation and theory suggests the

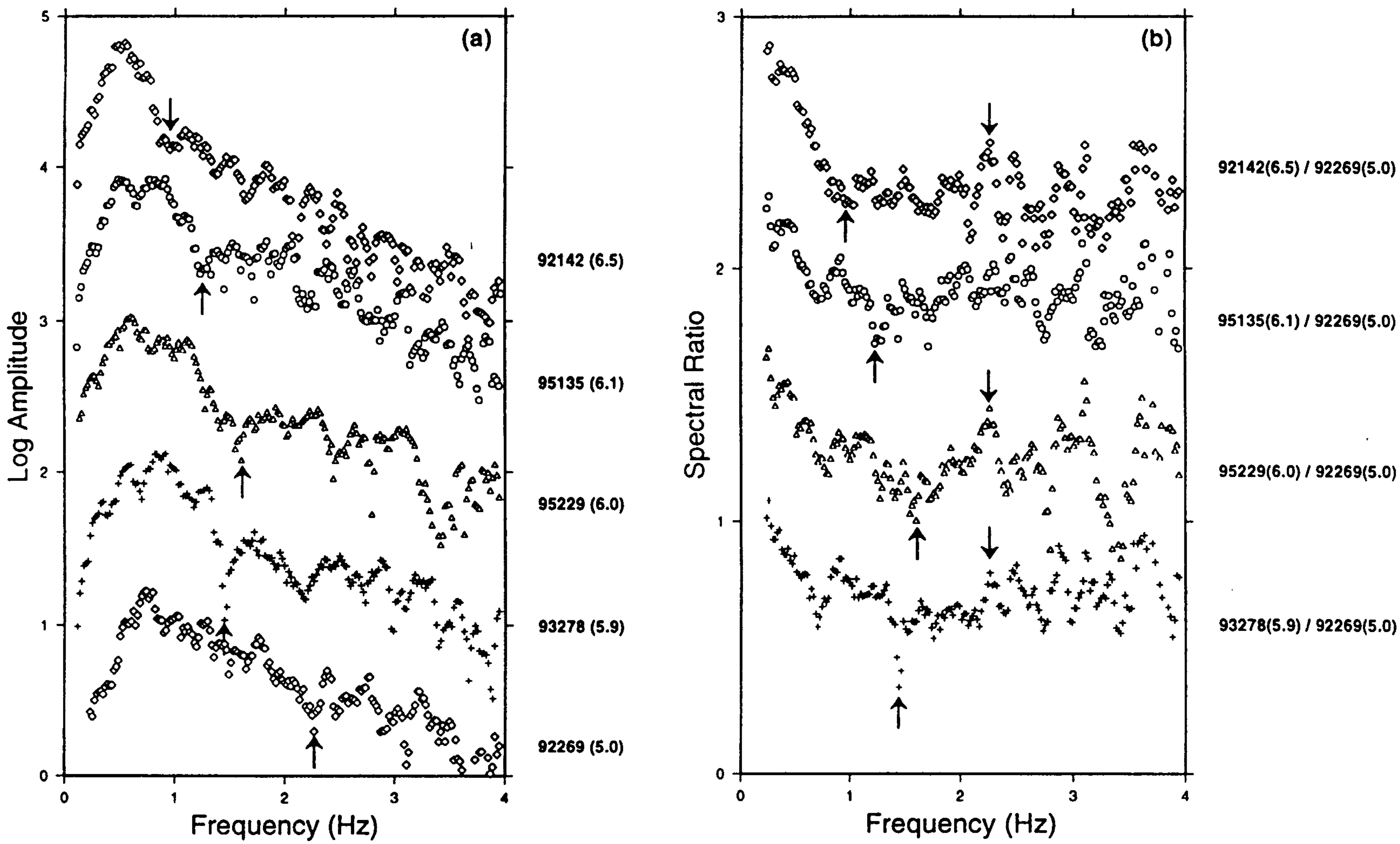

Figure 14. Results from 5 Lop Nor shots recorded at AAK. Both (a) spectra of Lg and (b) spectral ratios indicate the same spectral nulls (indicated by arrows) and a general increase in null frequency with decrease in m_b.

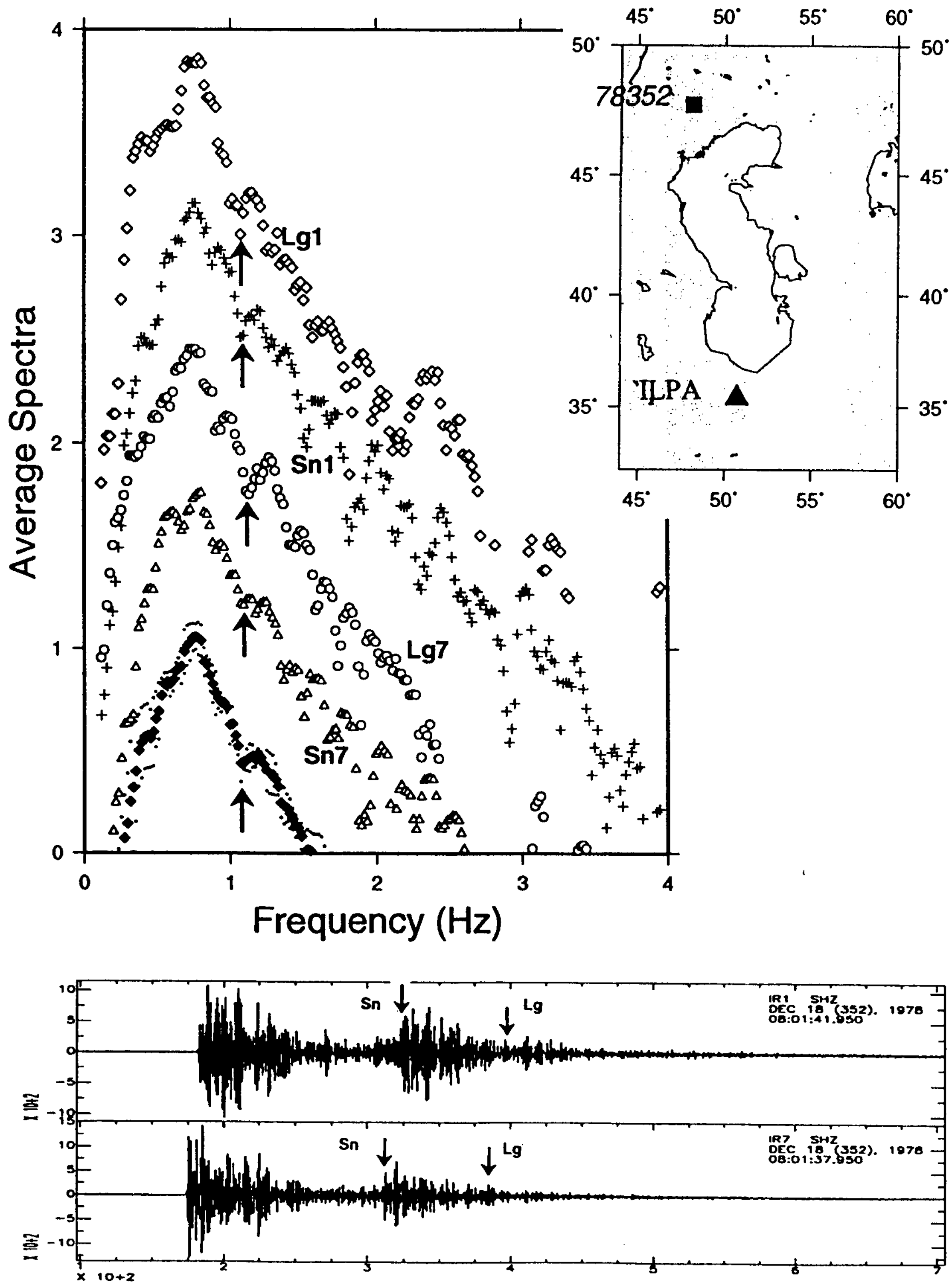

Figure 15. Waveforms and spectra of Lg and Sn from the Azgir PNE (78352) recorded at two ILPA sensors. The four spectra and their average indicate a distinct null at about 1.1 Hz, perhaps due to near-source scattering of explosion-generated Rg into S.

effective CLVD source to be at about one-third the shot depth. Dependence of the Lg spectral nulls on shot depth and local velocity structure provides a method for determining source parameters by comparing theory with observation. Preliminary results from an Azgir PNE also indicate that the near-source scattering of Rg may also make significant contribution to other S phases, such as Sn.

It is recommended that the broadband characteristics of not only Lg but also other phases (especially Sn and Pg) be investigated under various geological settings so that the role of near-source scattering of explosion-generated Rg is clearly understood and exploited for deriving source and near-source information. Representative sets of seismic data covering a wide range of known near-source parameters should be analyzed to understand the generation of both low and high frequency Lg and other regional phases. A comparison of the observations with synthetic seismograms (including finite-difference calculations) should be carried out so that the generation and propagation of regional phases are better understood. These studies will improve the seismic monitoring capability of regional phases by improving their reliability and transportability from one region to another.

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ACKNOWLEDGMENTS

In addition to the Principal Investigator, Tian-Run Zhang, David Salzberg, Claudia Carabajal, and Winston Chan contributed to this study. We sincerely thank William Walter of the Lawrence Livermore Laboratory and the IRIS staff for providing some of the data used in this study. Thanks are also due to Winston Chan and Wilmer Rivers for general guidance and a critical review of the manuscript.

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